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13. ABSTRACT *(Maximum 200 words)*
IN 1995 WE REPORTED EXPERIMENTAL RESULTS ON CHAOS SUPPRESSION (CONTROL OF CHAOTIC DYNAMICS) IN A NONLINEAR BUCKLED ELASTIC STRUCTURE AS WELL AS ANTI-CONTROL OF CHAOS IN THE VIRATIONS OF STRUCTURE WI5TH DRY FRICTION. IN 1996-1997 WE HAVE BEEN ABLE TO ACHIEVE THE SUPPRESSION OF CHAOTIC DYNAMICS FOR AN IMPACTING MECHANICAL OSCILLATOR USING A METHOD BASED ON THE IDEAS IN THE OGY CONTROL OF CHAOS THEORY. IMPACT IN LOOSE STRUCTURAL CONNECTIONS AS WELL AS IN MACHINE COMPONENTS SUCH AS GEARS HAVE BEEN SHOWN TO BE A SOURCE OF DETERMINISTIC NOISE IN THESE SYSTEMS. THE CONTROL OF THE IMPACT CHAOS WAS EFFECTED USING A DIGITALLY PULSED MAG ENETIC ACTUATOR.

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Final Report
to
Air Force Office of Scientific Research

1994-1997

Grant Number:
F49-620-94-0129

"Modern Methods for Low-Order Models
in Nonlinear Structural Dynamics"

Co-Principal Investigators:
Francis C. Moon
John F. Abel

Cornell University
Ithaca, New York

February 1998

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Objectives

The objectives of this research were to explore dynamics and control issues in nonlinear structures. The grant was motivated by the Air Force's long interest in space structures and deployable structures as well as fundamental questions concerning nonlinear dynamics in nonlinear structural systems.

The formal end of our AFOSR grant was to be January 1997, and the formal end of the ASSERT grant was to be June 1997. However, we asked for and received no-cost extensions. The AFOSR grant ended September 30, 1997 and we have extended the ASSERT grant until June 1998.

Accomplishments, 1994-1995:

We have successfully designed and implemented a "Controlling Chaos" system that can stabilize unsteady periodic motions in a nonlinear structure.

We have developed methods to analyze and control a cable actuated nonlinear deployable structure that could serve as a new class of adaptive structure robotic arms. This design uses the unique nonlinear structural properties of the elastica.

An object-oriented nonlinear dynamic analysis platform (ONDAP) code has been developed to analyze structural systems. It is based on a geometrically exact rod formulation (the so-called "Simo rod"). It has been used to study examples of the nonlinear dynamics of buckled structures under axial and lateral loads. In some applications, the object-oriented code converged with fewer degrees of freedom and longer time increments than a conventional finite element formulation.

We have shown that the proper orthogonal decomposition (POD) method can disclose information about the spatial modes that carry energy in a strongly nonlinear structure. The application of POD to weakly nonlinear structures seems to give the same information as the linear eigen modes.

Accomplishments, 1995-1996:

Our basic methodology has been to use experimental and computer simulation methods along with modern theory of nonlinear dynamical systems to investigate structural nonlinear problems. This methodology of nonlinear system identification has been summarized in two books (1987, 1992) the latest entitled *Chaotic and Fractal Dynamics*, J. Wiley and Sons. The research in 1995-1996 added to these techniques the method of proper orthogonal decomposition (POD) (earlier developed for structures by J. Cusumano of Penn State, an alumnus of our lab) and new techniques to control chaotic dynamics using small impulses.

The results of our work on control of a nonlinear deployable structure have been reported in a recent doctoral thesis by E. Catto, May 1996, Cornell University. This research has resulted in a unique controlled deployable flexible manipulator arm or structure based on the nonlinear theory of the elastica. This research has been reported at two conferences: one on Smart Structures (SPIE Vol. 2443 pp 171-181, San Diego, 1995) and a US-Japan meeting on Adaptive Structures (Key West, November 1995).

The second set of results on controlling chaos has resulted in a paper in the Journal of Bifurcation and Chaos (Vol. 6, No. 2, 1996, pp 337-347). Another paper on controlling friction chaos is in preparation. The results of these studies are unique in structural mechanics.

Accomplishments, 1996-97:

The accomplishments of the third year's effort can be summarized in four areas;

I. completion of object-oriented finite element code for simulation of nonlinear structural dynamics;

II. application of false nearest neighbor techniques to characterize chaotic dynamics;

III. application of statistical averaging technique to determine dynamical model for fluid-structural dynamics;

IV. new application of chaos control methods to structural impact dynamics.

I. Object-Oriented, Finite Element, Simulation of Geometrically Nonlinear Structures

In the last year we have finished work on a newly developed object-oriented finite element code for nonlinear dynamics analysis platform (ONDAP). The work was completed by former graduate student Dr. Victor Balopoulos under the guidance of Professor John Abel, the Co-principal investigator on this grant. This code was applied to large finite deformations of elastic rods and cables using geometrically exact formulations. One of the problems studied was the dynamic simulation of the stowage of a cable-controlled, hingeless, recoilable mast structure. This medium size problem, with hundreds of structural elements and nodes, exhibits bifurcations and limit points, closely spaced equilibria, and sensitivity to initial conditions. Good qualitative results are obtained and marked accuracy improvements are observed with discretization refinement.

II. Nonlinear Dynamics Measures to Characterize Structural Dynamics with Friction-like Brondary Conditions

One of the new signal processing methods to come out of nonlinear dynamics theory are methods to place an upper bound on the dimension of phase space of complex nonlinear systems. Such methods include fractal dimension calculations, Lyapunov exponents and a recent one called False Nearest Neighbors, or FNN. This method was developed by a group at University of California-San Diego, under Professor Henry Abarbanel. We have used this method to determine the phase space dimension of machine tool structures undergoing unwanted chatter dynamics. In recent research, graduate research assistant Duncan Calloway has studied the vibrations of a structure with a diamond end point as it scratches polymer and silicon surfaces. The application of nonlinear dynamics to materials processing is a growing field and should have important applications in aerospace manufacturing.

III. Fluid-Structural Nonlinear Dynamics

In a project largely supported by the Department of Energy, we have been studying the dynamics of a row of cylinders in cross flow. The goal of this study is to identify a nonlinear model for the fluid coupled dynamics. In this research, we have used a statistical averaging technique called ARMA (Auto Regressive Moving Average) to identify elements in the mathematical model. Experiments have also shown that this fluid-elastic system exhibits a sub-critical Hopf bifurcation route to flutter. We have recently developed a nonlinear system identification method which uses global bifurcation data such as subcritical vibration time history. This system might be a model to study aero-elastic flutter in jet engines.

IV. Control of Chaotic Dynamics

In 1995 we reported experimental results on chaos suppression (control of chaotic dynamics) in a nonlinear buckled elastic structure as well as anti-control of chaos in the vibrations of structure with dry friction. In 1996-1997 we have been able to achieve the suppression of chaotic dynamics for an *impacting* mechanical oscillator using a method based on the ideas in the OGY control of chaos theory. Impact in loose structural connections as well as in machine components such as gears have been shown to be a source of deterministic noise in these systems. The control of the impact chaos was effected using a digitally pulsed magnetic actuator.

Publications and Research Reports

S.G. Adams, F.M Bertsch, K.A. Shaw, P.G. Hartwell, N.C. MacDonald, and F.C. Moon, "Capacitance Based Tunable Micromechanical Resonators," *Transducers '95*, Sweeden (1995).

V. Balopoulos and J.F. Abel, "Parametric exploration of geometrically exact, numerically integrated C0 formulations for prismatic rods," *Computer and Structures*, submitted for publication, August 1997.

V. Balopoulos and J.F. Abel, "Use of shallow class hierarchies to facilitate object-oriented nonlinear structural simulations," in preparation for submission to *Finite Elements in Analysis and Design.*

V. Balopoulos and J.F. Abel, "On the challenge of simulating deployable space structures - A case study," in preparation for presentation and publication at the Structural Engineering World Congress, to be held in San Francisco, CA, July 18-23, 1998.

F. Benedettini and F.C. Moon, "Experimental dynamics of a hanging cable carrying two concentrated masses," *International Journal of Bifurcation and Chaos*, **5**(1), pp 145-157 (1995).

V. Bhatt and F.C. Moon, "Measures of robust dynamical behavior and fractal basin boundaries for two- and three-well potential problems," *AMD* **192**/*DE* **78**, *Nonlinear and Stochastic Dynamics*, ASME (1994).

E.S. Catto, F.C. Moon and C.K. Yuan, "Modeling of a cable actuated elastica manipulator," (submitted to *The International Journal of Robotics Research* 11/95), (1995).

E.S. Catto and F.C. Moon, "Robust control of a shape-changing flexible robot arm," (March 1995). Proceedings from *Smart Structures and Integrated Systems*, sponsored by The International Society for Optical Engineering.

J.P. Cusumano and F.C. Moon, "Chaotic non-planar vibrations of the thin elastics, part II: derivation and Analysis of a Low-Dimensional Model," *Journal of Sound and Vibration*, ***179*** (2), pp 209-226 (1995).

M.A. Davies and F.C. Moon, "Solitons, Chaos and Modal Interactions in Periodic Structures," in *Nonlinear Dynamics*, R. Rand 50th Anniversary Volume, A. Guran (ed.). World Scientific Publishers, 1997, pp. 119-143.

M.A. Davies, E. Catto and F.C. Moon, "Application of proper orthogonal decomposition to dynamics of nonlinear structures," (October 1994). Presented at the Mechanics Colloquium; Technical University, Darmstadt, Germany.

B. Feeny and F.C. Moon, "Chaos in a forced dry-friction oscillator: experiments and numerical modelling," *Journal of Sound and Vibration*, **170** (3), pp 303-323 (1994).

F.C. Moon and D.S. Callaway, "Experimental control of chaos in an impact oscillator," (October 1996) to be submitted to *J. Nonlinear Dynamics*.

F.C. Moon and D.S. Callaway, "Chaotic dynamics in scribing polycarbonate plates with a diamond cutter," (July 1997) to be submitted to *Phys. Lett. A*.

F.C. Moon and M.A. Johnson, "Nonlinear dynamics and chaos in manufacturing processes," in *Dynamics and Chaos in Manufacturing Processes* F.C. Moon, Ed., October 1997 (partially supported by NSF).

F.C. Moon, "Chaotic scattering of waves from nonlinear scatterers," *Acta Mechanica*, **107**, pp 153-169 (1994).

F.C. Moon, M.A. Johnson and W. T. Holmes, "Controlling Chaos in a Two-Well Oscillator," *International Journal of Bifurcation and Chaos*, Vol. 6, No. 2, 337-347 (1996)

F.C. Moon (ed.), "Nonlinear Dynamics and Material Processing and Manufacturing," Summary report on workshop given at University of California, San Diego (March 1995).

R. Pratap, S. Mukherjee and F.C. Moon, "Dynamic behavior of a bilinear hysteretic elasto-plastic oscillator, part I: free oscillations," *Journal of Sound and Vibration*, **172** (3), pp 321-337 (1994).

R. Pratap, S. Mukherjee and F.C. Moon, "Dynamic behavior of a bilinear hysteretic elasto-plastic oscillator, part II: oscillations under periodic impulse forcing," *Journal of Sound and Vibration*, **172** (3), pp 339-358 (1994).

A.P. Shanmugasundram and F.C. Moon, "Development of a Parallel Link Crane: Modeling and Control of a System with Unilateral Cable Constraints," (November 1995). (Presented at IMECE '95, San Francisco, November 1995.)

M. Thothadri and F.C. Moon, "Helical wave oscillations in a row of cylinders in cross flow," to appear in *J. Fluids & Structures* (1998) (partially supported by DOE).

Recent Books 1997

F.C. Moon (Editor). Nonlinear Dynamics and Chaos in Material Processing, J. Wiley & Sons (1998).

F.C. Moon. Applied Dynamics: An Introduction to Multi-Body Dynamics and Mechatronics, J. Wiley & Sons (1998).

Doctoral Theses 1994-1997

V. Balopoulos, "Object-Oriented Finite-Element Dynamic Simulation of Geometrically Nonlinear Space Structures," Ph.D. Dissertation, Cornell University, May 1997. (Also published as Structural Engineering Report 97-3, School of Civil & Environmental Engineering, Hollister Hall, Cornell University, Ithaca, NY 14853-3501, May 1997).

E. Catto, "Modelling and Control of a Cable Actuated Elastica Manipulator," Ph.D. Dissertation, Cornell University, May 1996.

M. Johnson, "Nonlinear Differential Equations with Delay as Models for Vibrations in the Machining of Metals," Ph.D. Dissertation, Cornell University, May 1996.

A. Shanmugasundram, "Design Dynamics and Control Issues in a Parallel Link Robot Crane - A System with Unilateral Cable Constraints," Ph.D. Dissertation, Cornell University, August 1995.

Personnel 1994-1997

F.C. Moon, Principal Investigator, Mechanical and Aerospace Engineering

J.F. Abel, Co-Principal Investigator, Civil and Environmental Engineering

Victor Balopoulos, Graduate Student (Graduates August 1997)

Peter Burke, Undergraduate Junior

Duncan Callaway, Graduate Student (from July 1996)

Erin Catto, Graduate Student (Graduated May 1996)

William Holmes, Research Engineer

Anil Reddy, Undergraduate Senior (Graduated, May 1996)

Arul Shanmugasundram, Ph.D., completed degree requirements July 1995, indirect support through lab technician

Igor Shnaper, Undergraduate Junior

Mani Thothadri, Ph.D. expected 1998, partial support from AFOSR

Honors and Awards

F.C. Moon - Elected to the National Academy of Engineering, 1996

F.C. Moon - Invited Lecturer (3 lectures) 4th International Symposium on Chaotic Dynamical Systems, Dutch Organization for Scientific Research, The Netherlands, 1994.

F.C. Moon - Plenary speaker joint ASME/JSME, Pressure Vessels and Piping Division ASME, Honolulu, 1995.

F.C. Moon - Keynote Lecturer, Brazilian Society of Mechanical Sciences Meeting on Dynamics, March 1997.

F.C. Moon, Keynote Lecturer, Belfer Symposium on Dynamics, Technion, Haifa, Israel, June 1997.

Professional Activities: Symposia and Workshops

F.C. Moon was the principal organizer of an International Union of Theoretical and Applied Mechanics Symposium (IUTAM) on New Applications of Nonlinear and Chaotic Dynamics which was held at Cornell University, July 27 - August 1, 1997. This week-long meeting consisted of 39 lectures, 19 poster presentations with nearly 90 participants from 19 countries. The Symposium involved three years of planning and organization with financial support from AFOSR, DOE, IUTAM and Cornell University.

Topics of papers relevant to AFOSR interests included papers on aircraft and helicopter dynamics, nonlinear structural dynamics, material processing, and control. Several AFOSR supported researchers were in attendance including F.C. Moon, A. Nayfeh, E. Dowell, and L. Virgin.

Moon also organized a workshop in 1995 at University of California, San Diego on Dynamics and Chaos in Manufacturing Processes which brought together many dynamics researchers and aerospace Engineers interested in manufacturing problems.

Research Communications and Dissemination

F. Moon organized two international meetings on nonlinear dynamics (IUTAM - Kyoto, August 1996 and IUTAM - Cornell, July 1997). Also, his books on nonlinear dynamics and chaos (1987, 1992) which summarize much of his research supported by AFOSR have been read by nearly 10,000 scientists and engineers.

The principal investigator, F.C. Moon, has given many invited lectures on nonlinear dynamics of solids and structures.

In the period 1987-1996, The Cornell Laboratory under F. Moon has produced 18 graduate degree holders (Table 1), more than half have gone to work for U.S. aerospace and high technology companies. These graduates have transferred the new methodology of nonlinear dynamics into an industrial setting.

TABLE 1

Graduates of the Cornell Laboratory of Nonlinear and Structural Dynamics
F.C. Moon, Director
1987 - 1996

Vivek Bhatt, Ph.D. (1994)	General Electric Research Lab
Erin Catto, Ph.D. (1996)	Parametrics Corporation
P-Z. Chang, Ph.D. (1991)	National Taiwan University
P-Y. Chen, Ph.D. (1990)	Chung-Shan Inst. of Sci. & Tech, Taiwan
George Scott Copeland, Ph.D. (1992)	United Technologies
Joseph Cusumano, Ph.D. (1988)	Pennsylvania State University
Matthew Davies, Ph.D. (1993)	N.I.S.T.
Brian Feeny, Ph.D. (1990)	Michigan State University
M. Farid Golnaraghi, Ph.D. (1988)	University of Waterloo
Mark Johnson, Ph.D. (1966)	General Electric Research Lab
G-X. Li, Ph.D. (1987)	Motorola Corporation
George Muntean, Ph.D. (1995)	Cummins Engines
Oliver O'Reilly, M.S. (1986) Ph.D. (1988)	University of California-Berkeley
Rudra Pratap, Ph.D. (1993)	Indian Inst of Science, Bangalore
Paul Schubring, M.S. (1993)	Intel Corporation
Arul Shanmugasandrum, Ph.D. (1995)	Applied Materials Corporation
Mani Thothadri, M.S. (1996)	Ph.D. Student
C-K Yuan, PhD. (1991)	Hua Fan College of Humanities & Tech., Taiwan